TAFONI IN THE EL CHORRO AREA, ANDALUCIA, SOUTHERN SPAIN

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ABSTRACT

Using a combination of field, laboratory and micromorphological evidence, this study examines tafoni (singular, tafone) in the El Chorro area of Andalucia, southern Spain, and makes inferences concerning the processes responsible for their formation. Twenty-five tafoni were randomly selected for field examination. The morphology of these cavernous rock domes is characterized by a helmet-shaped outer roof and an arched-shaped cavern, often with a partially overhanging visor; measurements of height, width and depth of the caverns revealed marked variations in size. The presence or absence of lichen cover, surface varnish, overhanging visor, cavern backwall stripes, rock flaking, weathering pits and cavern floor sediments was also noted.

Surface hardness values, obtained using a Schmidt hammer, are relatively low but significantly higher on the outer roof of the tafoni than on the inner cavern walls. Analysis of sediment samples collected from the cavern backwalls and floors indicates predominantly sandy textures, alkaline pH values and some base cation enrichment. Micromorphological analysis of thin sections, prepared from undisturbed blocks, reveals large quantities of pore-filling cement, consisting mainly of calcite, mineral grains affected by weathering and pseudomorphic replacement, and dark, rounded nodules with a metallic appearance.

In terms of their formation, different processes appear to act on different parts of the landform. On the outer roof surfaces, case hardening, resulting from near-surface cementation and surface varnish development, is dominant. On the inner cavern surfaces, however, core softening, resulting from granular disintegration and flaking, dominates. Exfoliation weathering, running water and wind deflation also appear to play an important role in tafone formation. A phased model of tafone evolution is proposed whereby the features pass through four phases of development–initiation, enlargement, amalgamation and degradation; in the study area there are examples of tafoni in each of these phases. Much of the evidence suggests that the tafoni are actively developing under current environmental conditions. © 1997 by John Wiley & Sons, Ltd.

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INTRODUCTION

Tafoni (singular, tafone) are typically cavernous weathering features which are several cubic metres in volume, and have arch-shaped entrances, concave inner walls, overhanging margins (visors) and fairly smooth, gently sloping, debris-covered floors (Cooke *et al*., 1993). They are found in many parts of the world, particularly in dry semi-arid environments including parts of Australia (Bradley *et al*., 1978), the Mediterranean region of Europe (Sancho and Benito, 1990), the northwestern Sahara (Smith, 1978), the US mid-west (Mustoe, 1983), the Namib desert (Ollier, 1978), and even Antarctica (Calkin and Cailleux, 1962) and coastal areas (Mottershead and Pye, 1994). Tafoni develop in a variety of rock types but are found chiefly in medium- and coarse-grained lithologies including granites, sandstones and limestones (Jennings, 1968).

The origin of tafoni is complex and likely to involve a combination of different processes, operating on different parts of the landform, though the marked similarity of form suggests a similarity of origin and development between regions. The cavernous hollows are believed to result largely from granular disintegration and flaking stimulated by a range of possible processes such as hydration, dissolution and reprecipitation of calcareous and saline cements, wetting and drying, rain-wash and wind deflation (Cooke *et*

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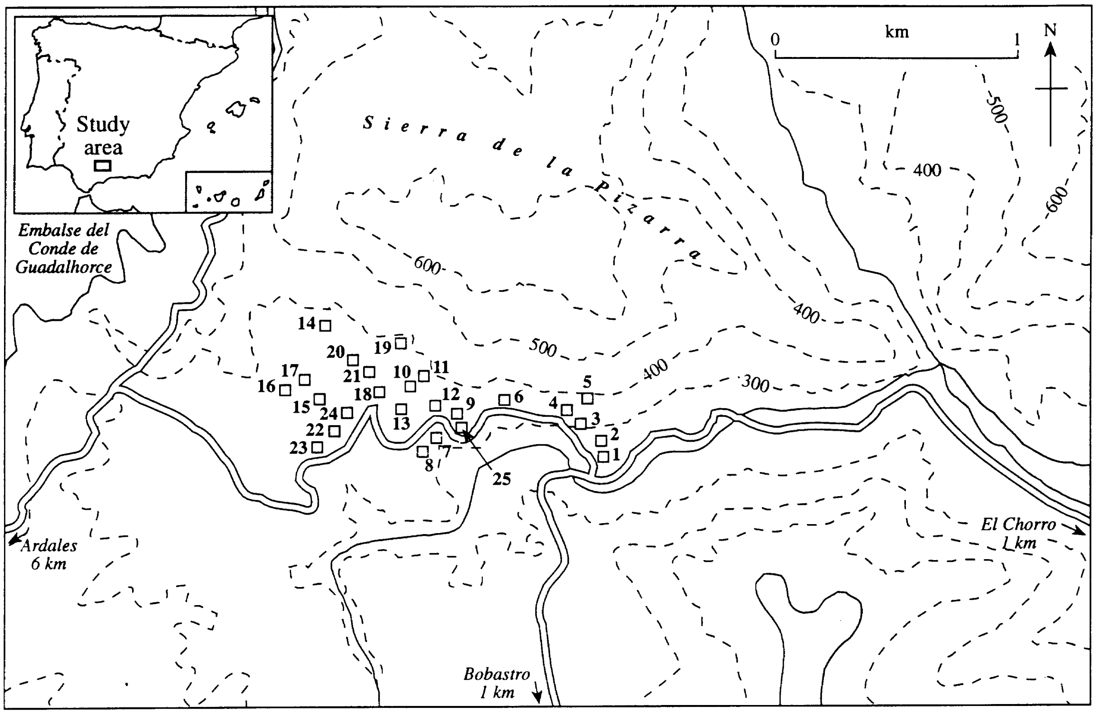


Figure 1. Map of the study area

al., 1993). Similarly, it has been suggested that the smooth and often rounded outer surfaces with their dark and hardened surface crust develop by case hardening, which may involve a combination of near-surface cementation, resulting from precipitation of salts drawn to the surface by capillary action, thermal expansion and contraction, and the formation of a surface rock varnish or mineralized coating (Cooke *et al*., 1993). Other factors which may be important in the development of tafoni include contrasts in microclimate (temperature, relative humidity and moisture) between the inner cavern and outer surfaces of the features, and the common presence of a lichen cover on the outer surfaces (Martini, 1978).

At the larger scale, geological factors (especially jointing and bedding patterns), topography (particularly slope angle and aspect), and hydrological controls (notably the presence of spring or seepage lines) are considered important in attempts to explain the spatial distribution of tafoni (Cooke *et al*., 1993). In terms of the temporal evolution of tafoni, the question as to whether they are active or relict features should also be addressed. Martini (1978) indicates that active tafoni are characterized by the presence of easily detachable flakes and fragments of fresh rock on cavern walls, and fresh debris on cavern floors. In contrast, relict examples are characterized by lichen-covered caverns and outer surfaces, and absence of cavern floor debris.

Using a combination of field, laboratory and micromorphological evidence from a sample of tafoni in the El Chorro area of Andalucia, southern Spain, the aims of this paper are as follows:

- to determine the morphological characteristics of the landforms;
- to identify the dominant processes responsible for their formation;
- to establish the temporal sequence of their development from initiation to degradation;
- to ascertain whether they are actively developing or relict features.

STUDY AREA

The El Chorro area is located in the upper part of the Guadalhorce valley approximately 50 km NW of Malaga (Figure 1). Geologically the area is dominated by limestones, mudstones and ‘flysch’ deposits of Jurassic and Tertiary age. These rocks were intensely faulted and folded during the Alpine orogeny and form part of the

Baetic Cordillera tectonic unit which stretches from southwest to northeast across the southern part of the Iberian peninsula. The tafoni are best developed in the flysch deposits, which consist predominantly of poorly sorted calcareous sandstones, grits and conglomerates (ITGE, 1990). The flysch deposits form a mainly south-facing slope which rises to the Sierra de la Pizarra. The slope is dissected into a series of valley and crest formations which are usually less than 100 m in length and 10 m in depth/height; the valleys lead into an ephemeral stream system, the Arroyo del Granado. The smooth, rounded nature of rock surfaces on the slope, together with the presence of surface rock debris, partially detached rock slabs and characteristic ‘onion skin’ features, some of which are several metres across, suggest that exfoliation processes are dominant.

Soil cover is generally thin and bare rock surfaces are widespread, particularly on the steeper slope and crest areas, probably reflecting the erosive effect of intense rainfall events. Vegetation cover is patchy and sparse, with tussocks of grasses and herbaceous shrubs forming a low maquis type of vegetation. On less steep slopes and in the valley bottoms, where soils are thicker, open woodland dominated by umbrella pine (*Pinus pinea*) is more common; much of the umbrella pine has been planted during the last 30 years as part of the Andalucian Forestry Policy (Agenica de Medio Ambiente, 1989). The area has a Mediterranean climate with a hot, dry summer and a mild, rather wetter winter. The nearest meteorological station is Estacion de Gobantes (8 km NE of the study area) which has mean temperatures of 11°C in January and 26°C in July. Absolute maximum and minimum temperatures are 41°C and –1°C, respectively, and indicate the extremes of temperature found in this area and the occasional occurrence of frost. Mean annual rainfall is about 500 mm, much of which falls between November and April with a tendency towards a spring maximum. Rainfall, however, is highly variable from year to year (Gomez-Moreno, 1989) and, as in December 1990 and 1995, values in excess of 100 mm have been recorded during individual rainfall events.

METHODOLOGY

Field observations

Fieldwork was carried out during August and September 1993. An initial reconnaissance survey of the study area identified about 200 tafoni in total. All of these were numbered and a random sample of 25 selected for detailed investigation. It is important to note that some tafoni, particularly those on the upper slopes of the field area, were inaccessible owing to slope steepness, while others had been strongly influenced by human activities, including road building and conversion to cave dwellings by additional excavation and construction of a front wall: these were excluded from study. The most accessible tafoni occurred between the Bobastro road junction and the K5 kilometre stone, in the mid-slope area within about 300 m of the road (Figure 1).

In order to gain some insight into local geological, topographic and hydrological controls on their formation, the area immediately surrounding each of the 25 sample tafoni was examined in terms of its lithology, jointing and bedding patterns, slope angle and aspect, and the presence or absence of spring and seepage areas. Each of the 25 tafoni was then examined to provide details of its morphological characteristics and surface hardness. The morphological characteristics determined were height, width and depth of the cavern, and vertical cross-sections of the cavern taken at quartile widths. The presence or absence of lichen cover, surface varnish, overhanging visor, cavern backwall stripes, rock flaking, weathering pits and cavern floor sediments was also noted. This information was used to examine the morphological variability of the tafoni, and to assess whether the features are currently active in terms of their development.

Surface hardness was determined using a Schmidt hammer, a technique used in previous studies of cavernous weathering (e.g. Campbell, 1991). Readings were taken to assess whether the outer roof surfaces of the tafoni were significantly harder than the inner cavern walls. Nine readings were taken (three sample points with three readings from the corners of a 5 cm triangle centred on each point) from the cavern backwall and outer roof (not including the overhanging visor) of each tafone.

Laboratory analysis

Bulk samples of loosely adhering and unconsolidated sediment were collected from the cavern backwall and floor, respectively, of ten tafoni, randomly selected from the 25 features examined above. These were oven-

dried and lightly crushed using a mortar and rubber pestle, and the following characteristics were determined: particle size distribution, pH and soluble base cation content (Ca^{2+}, K^+, Na^+). Particle size distribution was determined by passing a 100 g sample through a nest of sieves (2 mm down to 0.06 mm). Sample pH was determined using a Jenway pH probe on 10 g of sample suspended in 25 ml of distilled water. Soluble base cations, together with those adsorbed on fine mineral particles, were extracted using ammonium acetate, and their amounts determined using flame photometry. Together, these laboratory analyses should provide an insight into the physical and chemical characteristics of materials representing the source (cavern backwall) and product (cavern floor) of granular disintegration within tafone caverns.

Micromorphological analysis

Three undisturbed blocks were collected, and their orientation noted, from each of two tafoni, randomly selected from the ten features used for bulk sampling. These three were obtained from the outer crust, dark backwall stripe and light backwall stripe areas, respectively. The blocks were impregnated with a resin–hardener mix, and thin sections were prepared for micromorphological analysis. This approach allows microscale examination of the materials comprising various parts of the tafoni, and may permit observation of the dissolution and precipitation of cementing materials, the development of mineralized surface varnish and other related weathering processes.

In addition to general observations under plane- and cross-polarized light, and incident light, quantitative information was obtained by point-counting (250 counts per slide): first, within randomly selected grids on the microscope slides; and second, at 5 mm intervals along slide transects. The grid counts provide an indication of the relative proportions of different features on the slides, whereas the transect counts allow observations of changes from one part of the slide to another, for example, across the outer crust–inner cavern margin. This approach is commonly used in pedological investigations (e.g. Mellor, 1986) but is rarely adopted in weathering studies of this type.

RESULTS

Field relationships

Although the flysch deposits are often massively bedded and weakly jointed, a number of the sample tafone caverns appear to be associated with the more prominent bedding planes and joints. There is no apparent relationship, however, between the size or shape of the caverns and the location of such structures. Some of the tafoni, usually no more than three or four, occur in line across the slope following the general direction of bedding (e.g. features 10, 20 and 21, see Figure 1). This pattern is not consistent, however, since other similar linear arrangements are discordant with bedding (e.g. features 22, 23 and 24). Lithology of the flysch deposits is relatively homogeneous, with minimal variation between different tafone locations, and although texture is highly variable, changes are generally associated with bedding patterns. Such textural changes can be observed in the cavern walls of a number of tafoni, and where some of the larger stones become detached from the cavern wall, weathering pits can develop.

Slope angle in the vicinity of the 25 sample tafoni is in the range 10–30°. There is no apparent relationship, however, between slope steepness and size or shape of the tafone caverns. Since most of these are on the accessible south-facing slope, it is not surprising that 19 of the 25 sampled have an aspect between 135° and 225° (SE–SW). The six remaining caverns have an aspect between 247° and 315° (WSW–NW). It should be noted, however, that tafoni are well developed on some steep and inaccessible north-facing slopes on the south side of the valley. The relationship between present hydrological conditions and tafone location is questionable since no springs or spring lines were observed in the study area, and water flow in the adjacent streams and tributary gullies occurs only during and after larger rainfall events.

Tafone morphology

Although there are minor variations in form, most of the 25 tafoni sampled conform with the description outlined in the introduction (Cooke *et al*., 1993) (Figure 2a). The mean height of the cavern is 4·06 m (standard

(a)

(b)

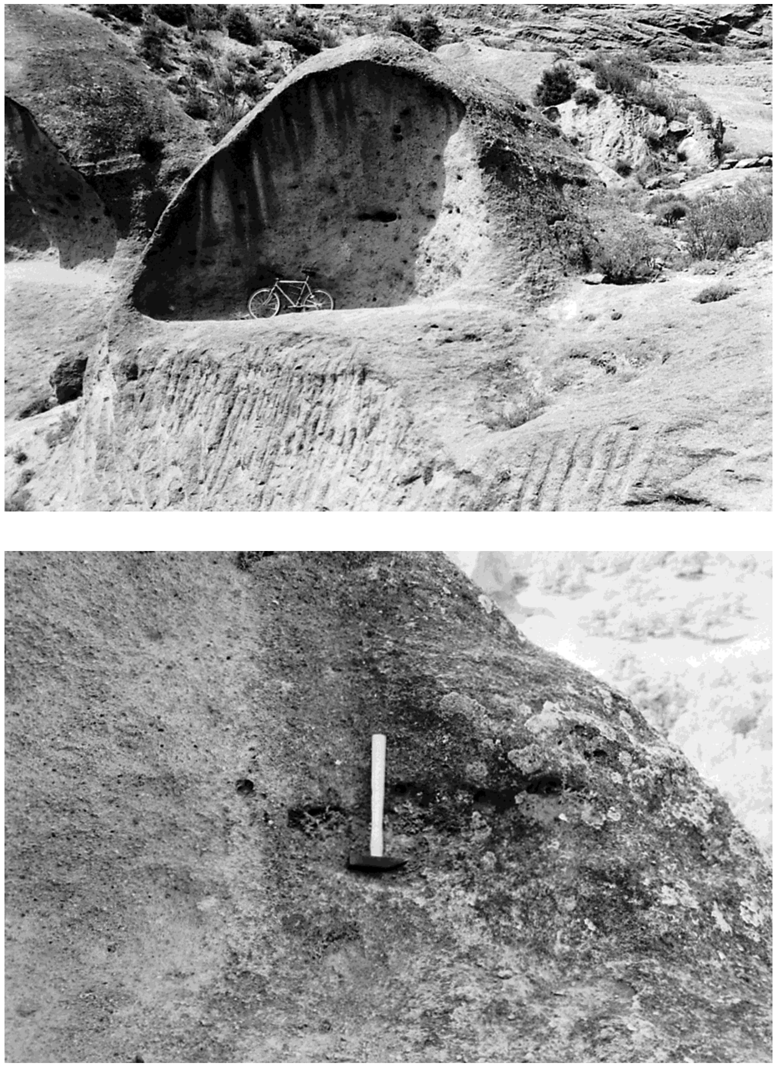


Figure 2. (a) An example of the characteristic tafone landform. (b) Boundary between dark, lichen-covered outer crust and lighter inner cavern surface

deviation, SD = 2·10 m), while the mean width across the front of the cavern and the mean depth of the cavern from front to back are 8·43 m (SD = 5·2 m) and 2·49 m (SD = 1·24 m), respectively. The largest cavern is 10·00 m high, 15·00 m wide and 0·5 m deep, and the smallest is 1·5 m high, 1·8 m wide and 0·6 m deep. Vertical cross-sections show the characteristic morphology of the caverns, with their curved backwalls, flat floors and overhanging visors (Figure 3).

Lichens cover the darkened outer surfaces of all the tafoni sampled, but are generally absent from the lighter coloured inner cavern walls (Figure 2b, Table I). The upper backwalls of many tafoni contain alternating dark and light stripes which run in a vertical direction (Figure 4a). The dark stripes often protrude from the backwall surface by up to 10 cm and sometimes possess a cover of lichens. They tend to be superficial in character, however, and are underlain by lighter, more friable material comparable to that of the lighter stripes. The lighter stripes are very friable and contain salt precipitates. On close inspection, the darkened outer surfaces of the tafoni and dark stripes often possess a varnish consisting of very small dark nodules. Unlike the exposed outer surfaces, the cavern walls are shaded for much of the time. They also show extensive flaking and mineral disaggregation (Figure 4b), and weathering pits are common. Most of the cavern floors are covered with a layer of unconsolidated sediment (Figure 4a), which may be several centimetres in thickness and in some cases is dissected by small channels.

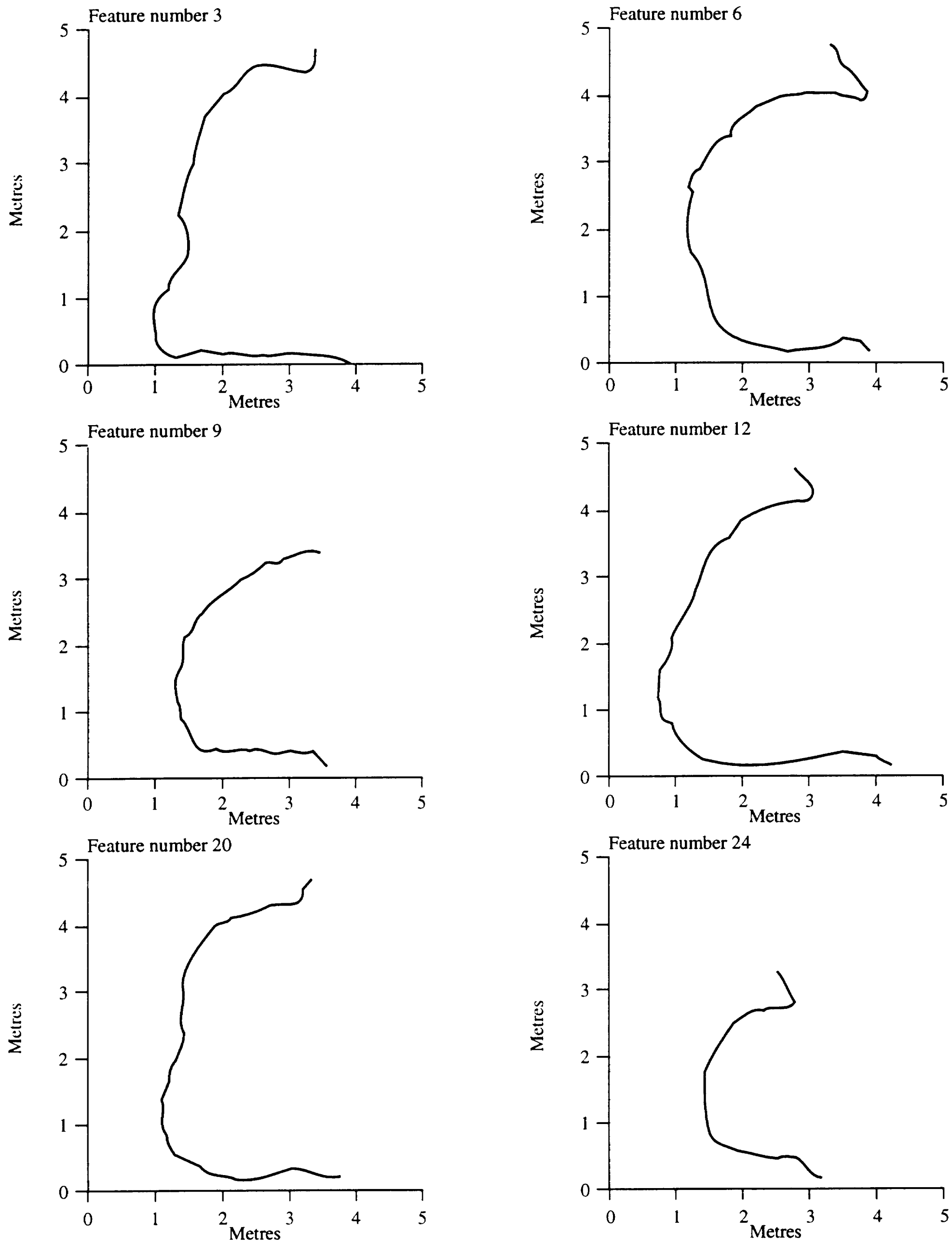


Figure 3. Vertical cross-sections of six randomly selected tafone caverns

Surface hardness

The hardnesses of the cavern backwall and outer roof surfaces were compared using a Schmidt hammer. All values were low (10–20) and some readings could not be obtained owing to the friable nature of the materials resulting from flaking and exfoliation. Values appeared higher on the outer roof surfaces (mean = 14·0, SD = 2·0, n = 19) than on the cavern backwalls (mean = 12·9, SD = 1·3, n = 19). As the data sets were normally distributed, a Student's t test was conducted to establish whether or not this difference was statistically significant. The result

Table I. Presence or absence of selected features on the 25 sample tafoni

Feature number	Cavern visor	Surface varnish on outer roof	Lichens on cavern backwall	Cavern backwall stripes	Cavern backwall flaking	Cavern floor sediments	Cavern backwall weathering pits
1	√	√	×	√	×	√	√
2	×	√	×	√	×	×	√
3	√	√	×	√	√	√	√
4	√	√	×	√	√	√	√
5	×	√	×	√	√	√	√
6	√	√	×	√	√	√	√
7	√	√	√	√	√	√	√
8	√	√	×	√	×	√	×
9	√	√	×	√	√	√	√
10	×	√	×	×	√	√	√
11	√	√	×	√	√	√	×
12	√	√	×	√	√	√	√
13	√	√	×	√	√	√	×
14	√	√	×	√	√	√	×
15	√	√	×	√	√	√	√
16	√	√	×	√	√	√	√
17	√	√	√	√	√	√	√
18	√	√	√	×	√	√	×
19	√	√	√	√	√	√	√
20	√	√	×	√	√	√	×
21	√	√	×	√	√	√	√
22	√	√	×	√	√	√	√
23	√	√	√	√	√	√	×
24	√	√	×	√	√	√	×
25	√	√	×	√	×	×	√

of this analysis indicated that the outer roof surfaces were significantly harder than the inner cavern backwalls ($T=2{\cdot}4$, $p=0{\cdot}05$, DF = 30)

Laboratory analyses

Cavern backwall and floor sediments are similar in their particle size characteristics, exhibiting predominantly coarse sandy textures, with a mean gravel content of 17·6 per cent (SD = 8·3 per cent, $n=20$), a mean sand content of 77·8 per cent (SD = 8·1 per cent, $n=20$) and a mean silt + clay content of 4·6 per cent (SD = 1·9 per cent, $n=20$).

The soluble cation and pH results are shown in Figure 5. Of the soluble cations, Na^+ occurs in greatest quantities, followed by Ca^{2+} and then K^+. Cation contents are greater in the floor sediments than in the backwall samples, although amounts of Na^+ and K^+ in the floor sediments show a high degree of variation. A Student's *t* test analysis indicated that Ca^{2+} and Na^+ contents were significantly higher in cavern floor sediments than in cavern backwall sediments ($T=4{\cdot}32$, $p=0{\cdot}0005$ for Ca^{2+} and $T=2{\cdot}55$, $p=0{\cdot}031$ for Na^+, $n=10$), although this was not the case for K^+ ($T=1{\cdot}99$, $p=0{\cdot}078$, $n=10$). Both backwall and floor sediments are alkaline in character with pH values above 8·0 in all samples. In contrast to the cation contents, however, pH values are significantly higher in the backwall samples than in the floor sediments ($T=4{\cdot}39$, $p=0{\cdot}0003$, $n=10$).

Micromorphological analysis

In thin section, the flysch material appears highly porous with large quantities of calcite cement supporting larger mineral grains and rock fragments. The pore-filling cement consists predominantly of small 'sparry' calcite crystals (>5 μm in diameter) (Figure 6a). These are light beige in appearance under cross-polarized light and are characterized by high-order interference colours which impart a typical green or pink tinge to the crystals (Adams *et al*., 1984). Calcite also forms surface coatings around larger mineral grains and rock fragments and sometimes forms pseudomorphic replacements (Figure 6a). In addition to calcite, other unidentified salts, which appear very light in colour, can occupy pore spaces (Figure 6b). Some of the larger mineral grains and rock fragments have a shelly appearance, reflecting the marine origin of the flysch deposits

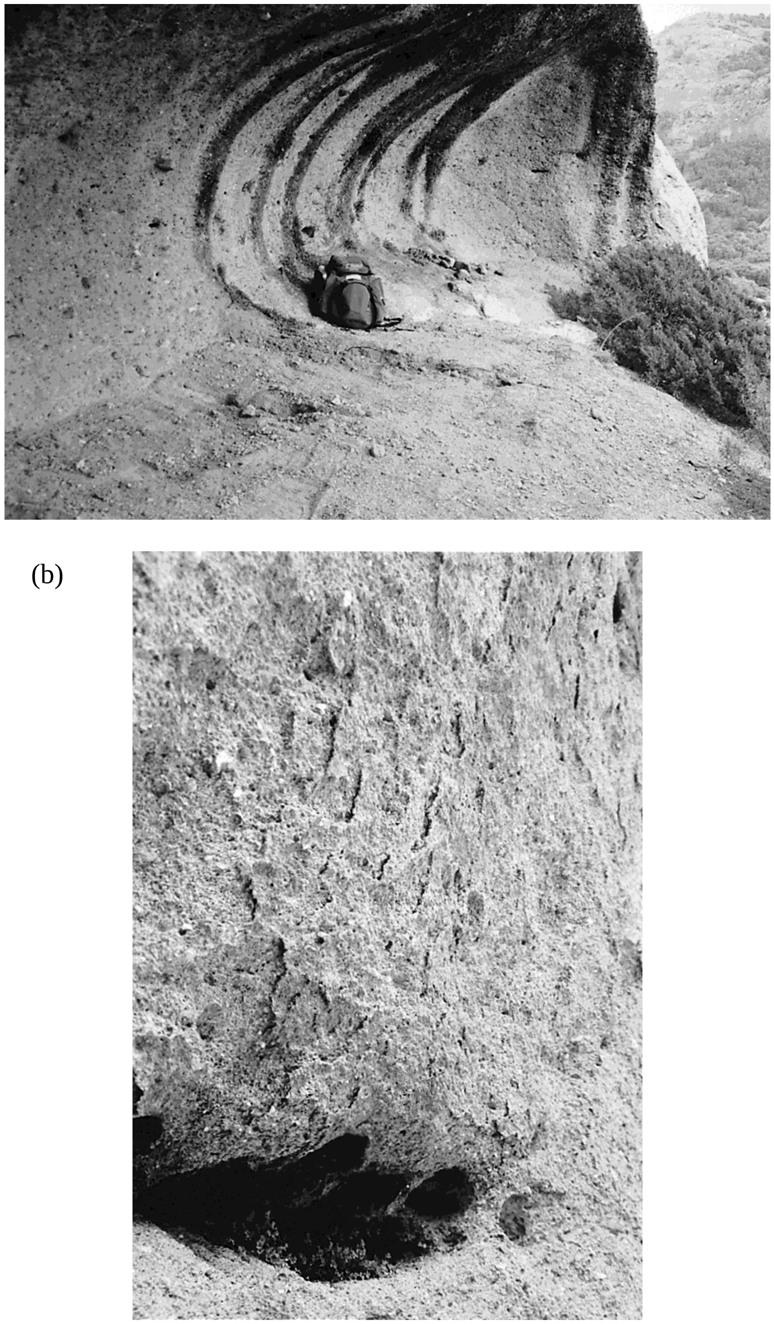
(a)
(b)


Figure 4. (a) Alternating light and dark stripes on upper cavern backwall, and sediment cover on cavern floor. (b) Flaking and mechanical disaggregation of cavern backwall material

(Figure 7a). Thin sections of the surface crust and dark backwall stripe areas reveal the presence of small, dark nodules which form a surface varnish (Figure 7b). Such nodules are absent from the remaining backwall and lighter stripe areas, where calcareous and saline precipitates are more common.

Point count analysis of grid squares, randomly selected from the thin sections, shows calcite and mineral grains/rock fragments to be the dominant features, together representing 70–80 per cent of the observations (Figure 8). Other features worthy of note include pseudomorphic grain replacement, pore space and unidentified salt precipitates, although none of these comprises more than 12 per cent of the observations. Point

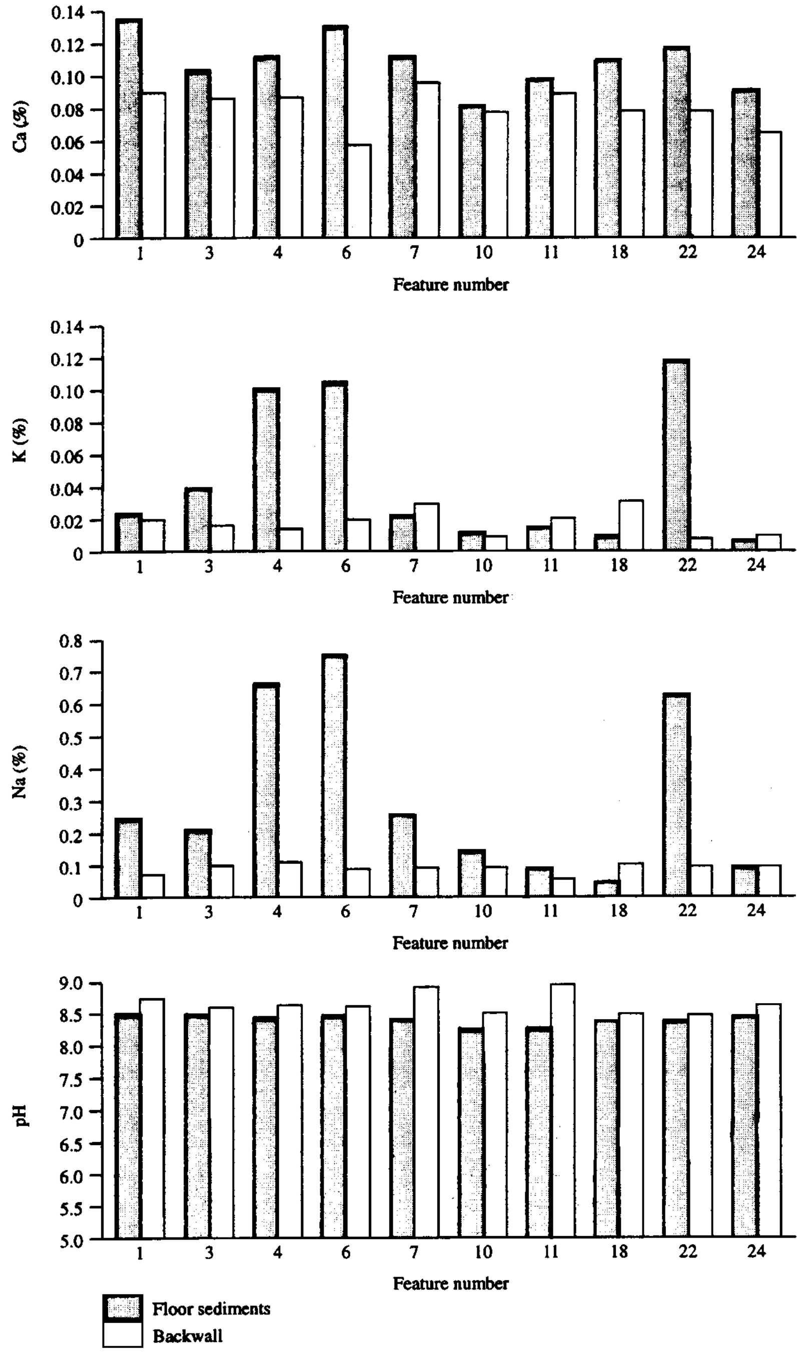
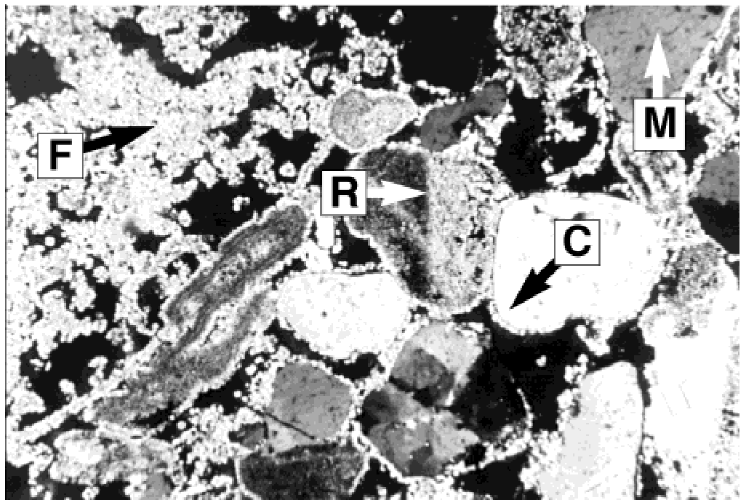


Figure 5. Soluble cation contents and pH of tafone cavern floor and backwall sediments

counts conducted along transects across the thin sections yielded results which were similar to the grid counts, with calcite and mineral grains/rock fragments representing the dominant features. No clear trends were identified along the transects.

(a)



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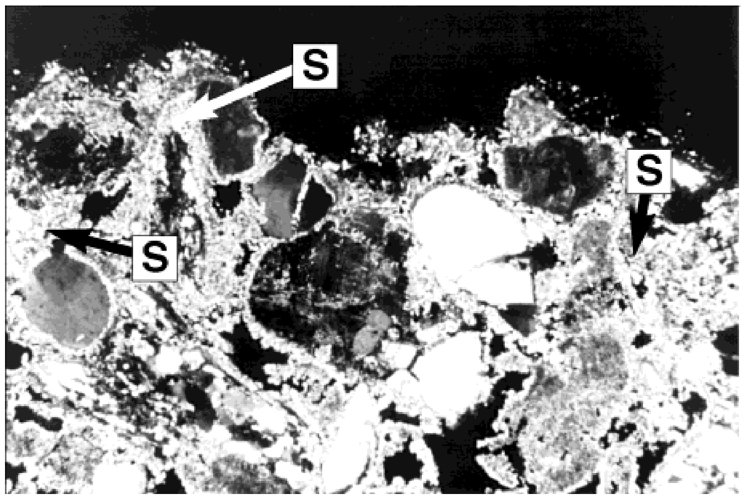


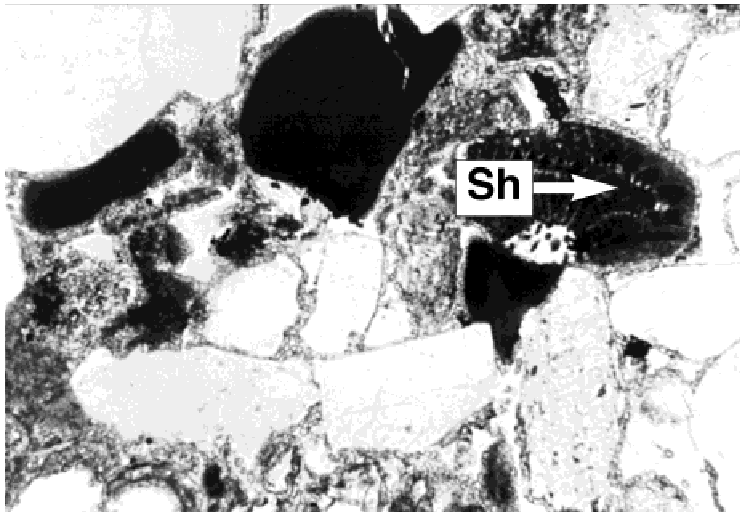
Figure 6. (a) Thin section photomicrograph showing pore-filling calcite cement (F), mineral grain (M), mineral grain coating of calcite (C) and pseudomorphic grain replacement (R). Taken under cross-polarized light. (b) Thin section photomicrograph showing in-filling of pore spaces with light coloured salts (S). Taken under cross-polarized light

DISCUSSION

Since a number of tafone caverns appear to be associated with prominent bedding planes and joints, it is possible that these structures exert some influence on tafone development. Such structures represent lines of weakness in the flysch deposits which can be exploited by incipient cavernous weathering, and may later provide a focus for tafone formation. In a study of tafoni on the coast of southwest England, Mottershead and Pye (1994) suggest that patination of joints plays a significant role in influencing the origin and morphology of tafoni. It should be noted, however, that the greenschist rock found in this area is more finely layered and jointed than the flysch deposits at El Chorro.

The results indicate that tafone formation involves a number of processes operating on different parts of the landform, and at different scales. Essentially, however, there appear to be two main groups of processes: first, 'case hardening' which leads to an increase in resistance and a decrease in permeability of the outer surface of the tafoni; and second, 'core softening' which leads to cavern enlargement through breakdown of the inner cavern walls and roof. The importance of these processes in tafone formation is supported by the Schmidt hammer results, which show that the outer roof surfaces are significantly harder than the inner cavern walls. It

(a)



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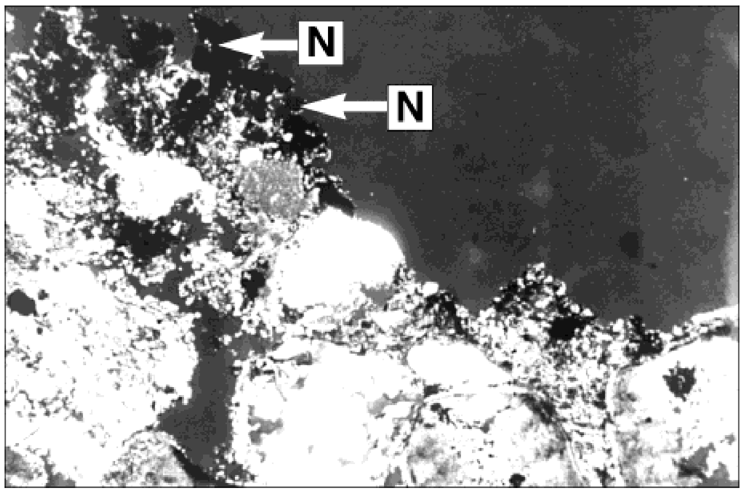

Figure 7. (a) Thin section photomicrograph showing shelly marine fragment (Sh). Taken under plane-polarized light. (b) Thin section photomicrograph showing dark nodules (N) with metallic appearance in surface varnish on an outer roof surface. Taken under cross-polarized light

should be noted, however, that this instrument was designed originally to test the resistance of construction materials, which are considerably harder than the flysch deposits in which the tafoni are developed. In fact, the reliability of the Schmidt hammer when used on soft, highly weathered rocks has been questioned (McCarroll, 1991). Running water may also be important through its contribution to weathering processes, erosion and transport of weathered particles, as may exfoliation and wind deflation. This discussion will focus on the roles of case hardening, core softening and running water in the formation of tafoni in the study area. It will also examine the stages of evolution of tafoni and whether they are largely active or relict features.

Case hardening

For much of the year the climate of the study area is characterized by high temperatures and low precipitation. The resulting intense evaporation is likely to encourage upward movement of soluble calcareous and saline materials by capillary action. As these materials are drawn towards the outer roof surfaces of the tafoni in solution, evaporation will lead to their precipitation in the form of a near-surface cement. The slightly alkaline nature of sediments from within tafone caverns, and the high content of soluble cations, particularly Ca^{2+} and Na^{+}, indicate the presence of calcareous and saline materials. Furthermore, micromorphological studies show calcite and other lighter coloured salts occupying much of the pore space in thin sections taken

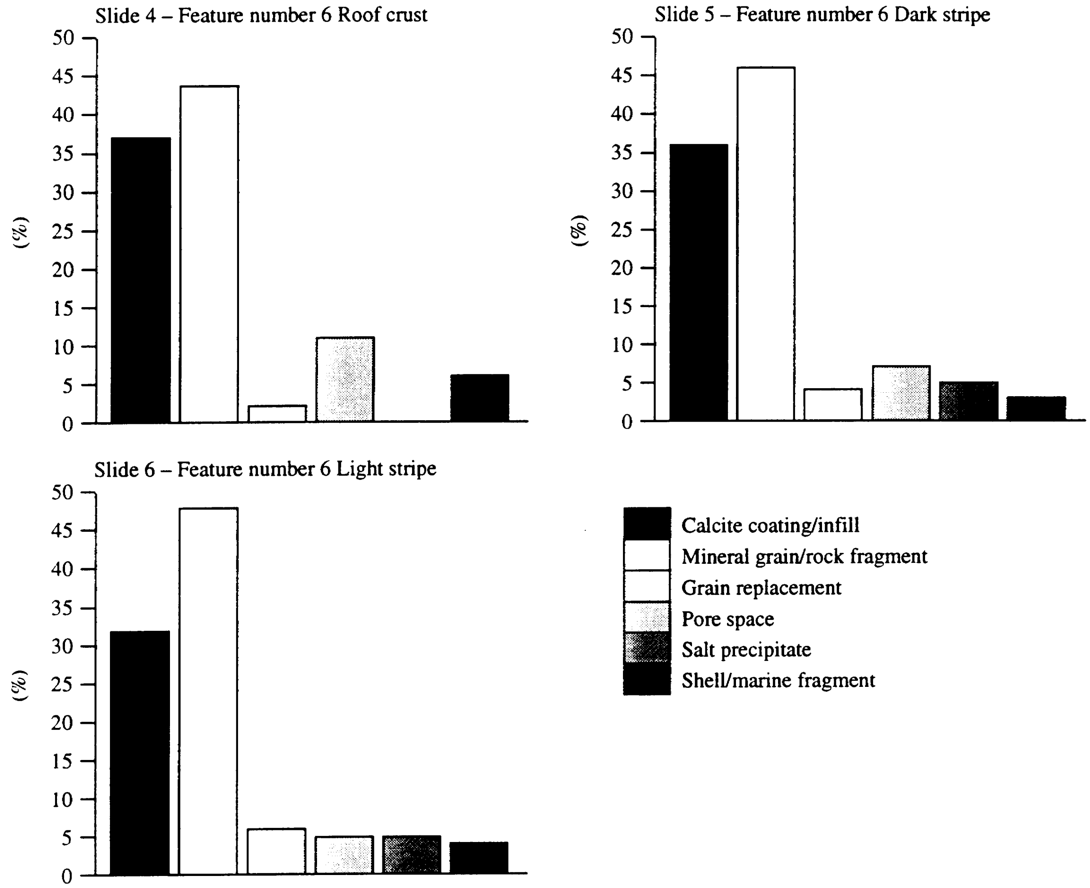

Figure 8. Random grid square point counts of thin section slides (250 counts per slide)

from within a few centimetres of the outer surface of the tafoni. Although the presence of these pore-filling materials appears to support the hypothesis of near-surface cementation, point count studies along transects across the thin sections do not reveal an increase in their frequency of occurrence towards the outer surface of the tafoni. However, identification of such a trend may prove difficult in thin sections which are themselves only a few centimetres in length.

Another form of case hardening involves the development of a mineralized coating or varnish on the outer surfaces of the tafoni. Unlike near-surface cementation, which affects the outer centimetres of the tafoni, the surface varnish is very thin and superficial in character, being only a few millimetres in thickness. Its formation is attributed to two main processes (Cooke *et al.*, 1993): first, a physicochemical process where Fe and Mn are drawn up from within the rock by capillary action and precipitated at the surface under dry, oxidizing and alkaline conditions; and second, a biological process where lichens and bacteria are responsible for fixing Mn at the surface. These organisms obtain energy from the oxidation of Mn during wet periods when they are most active.

Surface varnish appears to occur extensively on the outer surfaces of tafoni in the study area. These surfaces are considerably darker than the inner cavern walls, and close inspection of the surface reveals the presence of very small, black nodules. Micromorphological investigation confirms the presence of such nodular coatings which are superficial and appear metallic in character. Moreover, the dry, oxidizing and alkaline environment, and the fact that the outer surfaces of all tafoni examined are lichen-covered, indicate that conditions at the study area are ideally suited to surface varnish development. Martini (1978) refers to the surface varnish as an intense dark mantle with relatively low permeability; this serves to protect the underlying rock from dissolution

and salt weathering (Mustoe, 1983). It is possible that as surface varnish development progresses, the processes leading to case hardening become self-limiting, particularly those involving capillary action.

Core softening

The processes of core softening occur on the roofs and walls of tafone caverns rather than on their outer surfaces. Unlike the outer surfaces, the cavern areas are shaded for much of the time. Consequently, temperature variations and evaporation are likely to be lower, and relative humidities higher, in cavern areas. Increased relative humidity means that more water is available for weathering in these areas; the capacity for weathering is further increased due to the absence of both a protective surface varnish and a lichen cover. Weathering takes the form of flaking and granular disintegration, which occur extensively on the inner cavern walls and roofs of all the tafoni observed. The rock fragments and mineral grains accumulate on the cavern floors to form a layer of sediment with a predominantly coarse sandy texture, which may be several centimetres in thickness.

Crystal growth, associated with precipitation of $CaCO_3$ and salts, leads to mechanical disaggregation of rocks (Cooke *et al.*, 1993), and may promote flaking and granular disintegration in the tafone caverns. Dissolution of cements and the resulting disaggregation of the flysch deposits under moist conditions is also likely to promote these processes. The role of precipitation in core softening is further supported by micromorphological observations, which reveal large quantities of calcite and other unidentified salts in pore spaces of the flysch deposits. These observations also show extensive pseudomorphic replacement of primary mineral grains which may also contribute to core softening.

The presence of large amounts of $CaCO_3$ and other salts in cavern wall and floor sediments is also supported by the alkaline pH values and the high concentrations of base cations, particularly Ca^{2+} and Na^+. The relatively low concentration of K^+ reflects the limited presence of this cation in the parent flysch deposits. The patterns displayed by the base cation data are consistent with those of other studies (e.g. Mustoe, 1983; Young, 1987). Paradoxically, however, amounts of Ca^{2+} and Na^+ were significantly greater, while pH was significantly lower, in the cavern floor sediments than in sediment samples from the cavern walls. This difference is surprising, particularly since the cavern floor sediments are derived from the cavern walls and might therefore be expected to be similar in their chemistry. It may be explained by local enrichment of cavern floor sediments by bird droppings, and the urine and faeces of sheep and goats which sometimes seek shelter in the tafone caverns (Mottershead and Pye, 1994). In particular, the contribution of sheep urine to base cation enrichment, and subsequent nitrification-induced acidification, is well known from studies of pasture soils (e.g. Haynes and Williams, 1992).

Running water

The pattern of alternating light and dark stripes running vertically down the upper portion of cavern backwalls, and the channelization of cavern floor sediments, suggest that running water plays a significant role in tafone formation. During periods of heavy rainfall, water flows readily over the outer roof surfaces owing to their relatively low permeability. It then spills over the visor lip and, although much of it drips to the ground from here, significant quantities flow under the visor and down the backwall of the cavern (Douglas, pers. comm.); this water then runs onto the cavern floor sediments where it can create small channels. Such water flow may be responsible for the shaping of tafone caverns, as it can promote dissolution of cementing materials within the backwall sediments, and it can readily remove material loosened by flaking and granular disintegration. Once the characteristic cavern shape has developed, it may provide a focus for water flow during wet conditions, thus establishing a positive feedback mechanism of cavern enlargement.

As the water flows over the outer roof surfaces of the tafoni, dissolution of Mn and Fe in the surface varnish is likely to occur. These constituents are later precipitated out to form dark vertical stripes as the water flows over the drier and more porous cavern backwall sediments. The dark stripes protect the backwall surfaces beneath from further weathering, unlike the lighter stripe areas where granular disintegration and flaking is rapid. Lichens are rarely found in the tafone caverns, except on the dark stripe surfaces. It is possible, therefore, that lichens contribute to the formation of dark stripes through the biological fixation process outlined earlier.

Following an episode of water flow down the cavern backwall, lichens will tend to colonise those parts of the surface which remain damp for longest. Surface varnish formation will then be promoted in these zones through biological fixation of Mn, thus leading to formation of the dark stripes. During subsequent high intensity rainfall events, water will flow preferentially over the protective and less permeable dark stripe surfaces and onto the cavern floor sediments, where it will lead to the formation of small channels. In contrast, water will be absorbed in the more porous lighter stripe areas, thus contributing to dissolution of cements, granular disintegration and surface retreat. Consequently, the dark stripes often protrude from the backwall surfaces as the lighter stripes undergo retreat.

Tafone evolution

The evidence above indicates clearly that different processes are operating on different parts of the tafoni. On the outer roof surfaces, case hardening is dominant, occurring in response to near-surface precipitation of calcareous and saline cements, but perhaps more significantly due to surface varnish formation. Exfoliation weathering may also contribute to development of the characteristic ‘helmet-shaped’ outer roof of the tafoni. Evidence for exfoliation takes the form of hollow or detached portions of surface crust, and ‘onion skin’ weathering patterns observed on many rounded rock surfaces. On the inner cavern surfaces, granular disintegration and flaking occur in response to precipitation and dissolution of cements. Running water may also play a significant role in the shaping of tafone caverns during relatively rare wet periods.

At certain times of the year, particularly during the hot summer period, high winds are common. Wind activity may promote surface varnish development through increased evaporation and desiccation, whilst wind eddies within tafone caverns may mobilize floor sediments leading to the abrasion of backwall areas. Although frost is rare in the study area, it may contribute to mechanical disaggregation of the flysch deposits, particularly if it occurs after a period of prolonged or intense rainfall when the rock is saturated.

In an attempt to place the processes of tafone formation within the temporal context of landform evolution, a four-phase model of development is proposed:

(1) *Initiation*. The factors which lead to the initiation of tafoni are complex and unclear. Although there is no straightforward relationship between their location and geological, topographic or hydrological influences, patterns of bedding and jointing may be important in their initiation. Many flysch rock faces in the study area also contain small weathering pits (Figure 9a) which sometimes form a ‘honeycomb’ pattern. It is possible that tafone caverns may be initiated in such weathering pits, particularly where their enlargement is facilitated by natural weaknesses in the rock such as bedding planes or joints.

(2) *Enlargement*. Once the caverns begin to develop, a positive feedback mechanism is established whereby shading and elevated humidity promote further cavern enlargement through granular disintegration and flaking. Similarly, water flow down the cavern backwalls may increase as cavern enlargement progresses. The caverns are believed to enlarge in an upward and backward direction, whilst the flat cavern floors are possibly protected by their sediment cover. As the outer surface crust hardens through near-surface cementation and surface varnish formation, a negative feedback mechanism is established whereby the intensity of evaporation and capillary action, and surface permeability, are reduced. These processes, in combination with exfoliation and wind deflation, are likely to account for the characteristic helmet shape of the outer roof (Figure 9b).

(3) *Amalgamation*. As the tafoni develop, caverns may merge and weathering pits which develop on cavern walls may themselves enlarge to form small caverns within larger ones. In some instances, several large caverns may merge to form an elongated series of caverns (Figure 10a).

(4) *Degradation*. With continued cavern enlargement, the protective visors often become unstable and may collapse, leading to degradation of the tafoni and the formation of a small cliff face where the outline of former tafone caverns can be seen (Figure 10b). Once this occurs, the formerly protected inner cavern surfaces become exposed to rainfall, wind deflation, exfoliation, near-surface cementation, lichen colonization and surface varnish development, thus acquiring the characteristics of the outer roof surfaces.

Most of the evidence suggests that the tafoni observed in the study area are actively developing under current environmental conditions, rather than being relict features inherited from a past environment. The cavern walls

(a)

(b)

Figure 9. (a) Tafone caverns in the initial stages of formation, together with weathering pits on adjacent rock faces. (b) Large tafone cavern: note characteristic helmet shape, overhanging visor, dark stripes on upper backwall of cavern and exfoliation features below the cavern area

consist of freshly weathered and easily detachable rock fragments with no lichen cover, and the cavern floors possess a substantial sediment cover; all of these features are characteristic of actively developing tafoni (Martini, 1978). Inactive tafoni are characterized by dull cavern wall surfaces, with weathering pits and a cover of lichens and mosses, and absence of cavern floor sediments (Martini, 1978). It must be considered, however, that long-term variations in climate could affect tafone formation. An increase in precipitation could promote dissolution of cements and increased water flow, possibly leading to tafone degradation. Conversely, a decrease in precipitation may lead to increased salt precipitation and surface varnish formation. It is likely that the processes leading to tafone development have varied over time in response to climatic variations over the Quaternary period. They will also vary in response to shorter-term changes in climate, either over a period of several years or on a seasonal basis. All of the stages of tafone development can be observed in the study area, suggesting that the tafoni have been initiating, developing and degrading in the flysch deposits here for a long but unknown period of time.

(a)

(b)

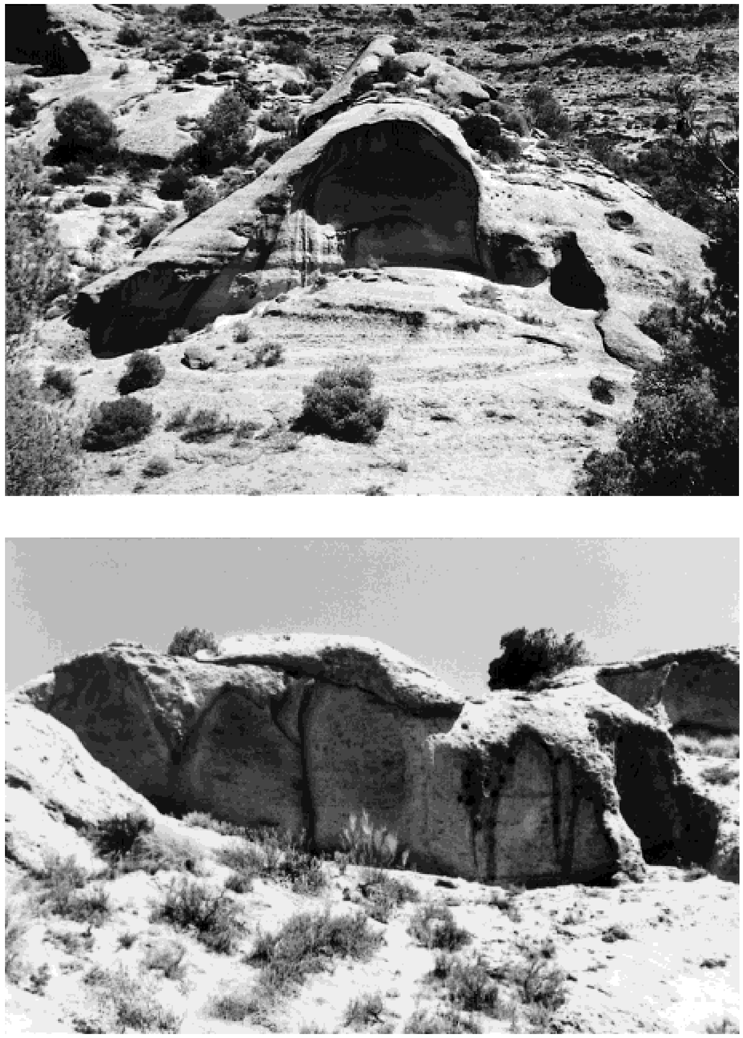

Figure 10. (a) Amalgamation of tafone caverns. (b) Degraded tafoni; although the cavern roofs have collapsed, the outline of former amalgamated caverns can be seen

CONCLUSIONS

This study has focused on the features relating to tafone formation in the El Chorro area of Andalucia, from which inferences have been made concerning processes. Morphologically, the tafoni are consistent with descriptions elsewhere in the literature. Characteristically they have a helmet-shaped outer roof and an arch-shaped cavern with an overhanging visor, curved walls and a flat, sediment-covered floor. The outer roof surfaces are relatively dark in appearance and are often covered with crustose lichens, unlike the lighter coloured inner cavern surfaces. Alternating light and dark stripes with a vertical orientation are observed on the upper portion of cavern backwalls of many tafoni.

Evidence from field observations, laboratory analysis of sediments and particularly from micro-morphological studies, indicates that different processes are operating on different parts of the tafoni. On the outer roof surfaces, case hardening is dominant and involves near-surface cementation and surface varnish development. On the inner cavern surfaces, core softening dominates, with flaking and granular disintegration

occurring in response to dissolution and precipitation of cementing materials. Exfoliation weathering, running water and wind deflation also appear to contribute to tafone formation.

It is possible that tafone formation is initiated at weak zones or points, such as bedding planes, joints or weathering pits, in the surface of the flysch deposits. As the caverns develop, shading and elevated humidity may promote core softening, which in turn leads to further cavern enlargement. Eventually, adjacent caverns merge and their protective visors may collapse. The degraded tafoni caverns are then exposed to the case hardening processes indicated earlier. This phased model of tafoni evolution may have been repeated several times in the study area, as indicated by the presence of tafoni in various stages of development. Most of the evidence suggests that the tafoni are developing actively at present and are not relict features inherited from a past environment.

It is suggested that future studies of tafone development should focus on detailed comparisons of outer roof and inner cavern materials and microenvironments. For example, the materials comprising these surfaces could be examined using scanning electron microscopy or electron microprobe analysis, in order to evaluate their nature and origins more fully. Such information, together with monitoring of differences in temperature and relative humidity between outer roof and inner cavern surfaces, may shed further light on the processes of case hardening and core softening. Similarly, the installation of erosion pins in cavern backwalls, and sediment traps on cavern floors, may allow the determination of rates of flaking and granular disintegration (Rice, pers. comm.). In addition, more detailed surveying and mapping of the field area is required in order to evaluate the influence of mesoscale controls, such as geology, topography and hydrology, on the location, spatial distribution and morphological evolution of tafoni.

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